STRESS ANALYSIS OF KNEE JOINT AND KNEE PROSTHESIS

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Bachelor of Technology

In

Biomedical Engineering

By

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CERTIFICATE

This is to certify that the thesis entitled "**Stress analysis of knee joint and knee prosthesis**" by **JHARANA DEORIYA (110bm0005)** submitted to National Institute of Technology, Rourkela for the award of Bachelor of Technology in Biomedical Engineering during the session of 2010-2014 is a record of bonafied work carried out by her in the Department of Biotechnology and Medical Engineering under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other university / Institute for the award of any Degree.

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ABSTRACT

Knee joint consists of different components, i.e. femur, tibia, patella and menisci which make it a complex structure, undergoing different critical loads in human body performing motions and physical activities. The present study focuses on the analysis of stress magnitude on knee joint and knee implant when these are introduced with different loads acting upon it with varying angles of inclination. 3-D model of the knee joint and knee implant were designed using 3-D modeling software i.e. CAD. These models were imported to ANSYS to get the specific results of stress magnitude using finite element analysis. This study has revealed that with a load range of 540N to 790 N and change in angle from 10° to 90°, the knee implant could be able to sustain a load of 540-640 N at an angle of 10°-50° demonstrating a stable stress value of 1.27E+08 – 6.11E+08 Pa. At steady state of the knee i.e. when the knee is at 90° position, stress value reaches to 1.28E+08 Pa. When this study was compared with stress analysis of the knee joint without implant it was observed that there is wide variation in the stress magnitude with the increase in load values and changing angles. At load of 690-790 N, the wearing effect become lesser at 10°, 70 ° and 90° angle. At an angle of 50°, stress value attains a high peak bar with 7.47E+08 Pa when 690 N load is applied on the knee joint without an implant. The study depicts that the load and stress can be better managed by the application of implant rather than without an implant. Hence the design of implant must give emphasis on different types of material depending upon the amount of stress experienced at different location. Overall, the study provides a guideline for fabrication of prosthetic implant in the line of intimation with reduced number of experiments so that implants with better stress management and enhanced load bearing capacity can be designed.

Keywords: Knee joint, implants, finite element analysis, ANSYS, Von-misses Stress.

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Abbreviation

FEA Finite Element Analysis

3D Three Dimensional

mm mili meter

MPa Mega Pascal

nm nano meter

o degree

Pa Pascal

wrt with respect to

N Newton

Sec Second

Nm Newton-meter

F Force

M Moment

CHAPTER- 1

Introduction

The knee joint is complex structure in the human body which undergoes critical loading simultaneously while performing different physical activities such as walking, running, in rotational motion, sitting, static positions etc. what we used to do in our day to day life. Major parts in a knee joint are femur, tibia, patella and meniscus. It has two articulation components one is in between the tibia and femur and another between the femur and patella. The knee joint is a pivot hinge joint. It permits extension and flexion of leg with that rotation in both internal as well as external part [1]. It‘s articular bodies are lateral and medial condyle were patella is present in the posterior region in between the lateral and medial condyle surfaces. Articular capsule of knee joints are the fibrous membrane and synovial membranes. Synovial membranes are those which are been attached near the cartilage of both tibia and femur. Cartilage is elastic thin tissue that acts as protection guard for bone and makes the joint surfaces. In knee joint there are two types of cartilages joint one is fibrous cartilage and other as hyaline cartilage. Fibrous cartilage has resistance to high pressure and has high tensile strength [2] . A meniscus is the articular disk present in the knee joint, having two components i.e. medial and lateral meniscus.

Knee Prosthesis:

In the field of medicine prosthesis is defined as an artificial device which is replaced in the position of any defective body part or when any body part went missing because of trauma, disease or any congenital condition. Mainly two types of prosthesis are being used in i.e. craniofacial and somato (body). Craniofacial prosthesis is of two types i.e. extra oral prosthesis and intra prosthesis where as somato prosthesis are of many types like limb prosthesis, ear prosthesis any defective body parts when being replaced by an artificial organ [3].

History:

In our history prosthesis were mentioned frequently, such as an early prosthesis mentioned was in Rigvada a warrior queen Vishpala. Egyptian in their new kingdom found wooden toe on an individual body [4]. Likewise, in Rome piny the elder recorded that a Roman general without an arm had an iron hold to shield up from the battle. During the period of Renaissance, prosthetics were designed and developed by using steel, iron, wood and copper. Prosthetics came up to be functional during the age period of 1500s. An Italian surgeon has a record that an amputee had an artificial arm, which allows him and helped him to his take off hat, do a signature on the paper his name and open the purse. An above-knee device among other invented devices, those are foot prosthesis, kneeling peg leg with adjustable harness, and keeping the knee stable with a knee lock control. The functionality of his advancements showed how future prosthetics could develop. The NAS, at the end of World War II, (i.e. National Academy of Sciences) advocated for better development and further research in the field of prosthetics. Through the funding arranged by the government, a development and research program have been developed in specific zones, such as within the Navy, Army, the Veterans Administration, and in the Air Force.

Knee Replacement:

Knee replacement is also termed as knee anthroplasty. A surgical method of replacing the load bearing surfaces present in the knee joint so as to cure the pain bearing regions and disability areas of the joint [5]. Knee replacement is the surgical technique which has been carried out mostly during the cases like osteoarthritis. Other causes which may lead to pain in the knee joints are due to ligament tearing, cartilage defects, pain due to meniscus tearing etc. Knee replacement can be done using two methods i.e. by Total Knee Replacement and other is Partial Knee Replacement [6]. The principle of knee replacement technique is to remove those defective and damaged joint parts and surfaces of knee and replacing it with an implant made of metal and plastic.

Technique of Knee Replacement:

Knee replacement is a surgical method where initially a post operative method is being followed up so as to carry out the surgical method. In this first of all an X-Ray is done of the load bearing regions of knee joint for the knee replacement of both lateral and AP of knee with 30° flexion of knee were 30° flexion is done to see the narrowing occurred in between the joints of knee. With the X-Ray imaging, MRI is also done to see the cartilage effects and its defective regions to use to carry out the replacement and incorporating specific implant in that region. After that, the person going through the post operative exercises being asked to perform certain physical activities like motion of the hip, knee, rotation of knee, hip, walking, sit ups etc. before entering to the surgery. Image collected from X-ray should be accurate for the measurement of the size of the different components of the implant replacing the organ [7].

While undergoing surgery the front surface of the knee is exposed where the quadriceps muscle remains detached from the patella. As there is detachment of patella towards one side of the knee joint because of which femur and tibia get exposed at their distal and proximal end respectively. The AC and cartilages were removed were as the ligaments attached to tibia and femur were preserved [8]. After that implants were placed in between the bone and were fixed using PMMA cement. Without PMMA cement the method is termed as osseointegration which includes porous metals as implants.

Knee Replacement Implants:

When there occurs any damage in any bone or any joint parts of human body, to overcome those defective organs people generally prefer replacement of those with an specific artificial organ or as we can say implant as prescribed by the surgeon and going through an operative method. Knee replacement can be done by total knee replacement or some people get benefited with partial knee replacement. Implants are generally made up of metals, metal alloys, strong plastic materials, ceramic material which can be implanted in our body, to make the joint strengthened strong polymeric material like acrylic paste[9].

Implant Design:

There are several kinds of implant designs for knee replacement implants. As we know knee joint is a type of **hinge joint** because with the help of knee joint different motion as be performed by the leg like straightening and bending of legs[9]. There lots of flexion and extension motions are being carried out in the knee joint, which makes it a complex structure, were surfaces if bone generally glides and roll over each other. Accounting on this function of knee first implant designed was the hinge i.e. a connecting hinge was placed in between the parts of the knee joint. Newer implants were designed according to the complexity, durability, biocompatibility, its tensile strength etc. and to design it in such a manner so that it can mimic the actual functioning of the normal knee functions. Some of the implant models were designed modeled to preserve the actual ligament of the patient where as other parts were replaced by an artificial organ. Now days in the market area there are about 150 models of knee replacement implants design. Recent designed knee implant mostly focused on the gender specificity. According to different studies and research it was found that the portions and shape of women's knee is different from man's knee structure. So may manufacturers design knee implant with a attach thighbone component at the end so that it can easily match the knee structure of women knee joint. It provides better functioning than any standard implant[10]. Right choice of implant design can be used after the specification given by the doctor or surgeon according to the brand and model design as referred to ones weight, age, and health and activity level.

Implant components:

There are generally three components in a designed model of total knee replacement implant which are lower end of femur, total surface of tibia, and the back surface of patella. The **lower end of femur** made up of metal which curves around the end femur. It is inserted in such a manner so that the kneecap can move smoothly up and down when the knee does flexion and extension. The **top surface of tibia** made of a flat metal platform embedded with a cushion of strong, with a better tensile strength, compatibility in vivo and a high durability. Mostly used plastic material is **polyethylene.** Some of the implants are designed without those plastic material embedded in them those are porous implant. Polyethylene attaches to the bone surface directly. For the stability of the implant the stem of the component inserted into the center of the tibia bone. **Patella back surface component** is dome- shaped structure. Patella is made up of plastic material polyethylene's which duplicate the different shapes of structural design of Patella (i.e. the knee cap)[11].

Most of the patients get implanted with **fixed bearing implants** where the polyethylene a plastic material of tibia gets attached with the metal implant firmly beneath that surface of the implant. Femoral component rolls over the cushioned surface. Excessive load and simultaneous loading affects tearing of the fixed bearing prosthesis. As the wearing starts it causes pain at the implanted region leading to loosening of the implant from the target site[12]. These implants have longer durability with less tearing and wear effect. Another kind of implant device generally used as is mobile bearing implant, which uses three component devices that has been present in the knee joint for better movement of the knee joint with an implant. With this implant patient have better and do have a greater degree of rotation of the medial and lateral side of the knee. It acquires more support from soft tissue present at the target site. Mostly selection of biomaterials is based on the chemical, biological, mechanical and physical properties. Some the biomaterials that are being used in the designing of those implants are Co-Cr alloy, Ti alloy, and for the fixation of the implants with the bone UHMW polyethylene being used in[13].

Knee replacement implant devices/prosthetics **Device details:**

There are more than 150 types of knee replacement implants available today made by several manufacturers. The list below is representative of those available[14].

DePuy Orthopedics

- Sigma® High-Performance Partial Knees
- Sigma® Rotating Platform Knees
- Sigma® Fixed-Bearing Knees

Zimmer

- Zimmer Unicompartmental High-Flex Knee
- Zimmer Knee Solutions Patellofemoral Joint
- Nex-Gen LPS Flex Mobile
- LPS Mobile-Bearing Knee System

Biomet

- Cement less Vanguard® Complete Knee System
- Oxford Partial Knee

- Vanguard® Complete Knee System
- Vanguard® SSK Revision Knee System

Stryker - Triathlon Knee system Smith & Nephew

- ACCURIS minimally invasive unicompartmental knee replacement
- Genesis II CR and PS Knees
- Journey BCS
- Journey Deuce
- Journey PFJ
- Journey UNI

Wright Medical Technology

- ADVANCE STATURE® Knee
- ADVANCE® Double-High Knee
- ADVANCE® Medial-Pivot Knee
- EVOLUTION® Medial-Pivot Knee System
- ADVANCE® Unicompartmental Knee System
- LINK® MITUS® - Minimally Invasive Technique of Unicondylar Sled Prosthesis Endo-Model®
- ADVANCE® Revision Knee System
- ADVANCE® Stemmed Medial-Pivot Knee
- LINK® Endo-Model Rotational Knee System (Non-Modular)

CHAPTER- 2

Literature Review

Stress analysis is a discipline under engineering, an effective method to determine the strains and stress acting upon any material. Those materials are subjected to any particular load and forces in any direction. Stress analysis is used for keeping any specific structure in a functional state and maintaining its structure, with that investigating the causes which may lead to the failure and damage to that structure[15]. Stress analysis is done in any geometrically described structure with that checking the properties of the material used in that specific structure, where the loads being applied. Stress analysis can be done through computational analysis, mathematical techniques, and analytical, mathematical approach or combination of two three methods. Mechanical behavior of knee joints is a complex system. There are two states of mechanics in which the body behaves: one is the static state where body in a system is acting on a constant motion, it's either at a rest state or moving with a constant velocity[16]. The other state of the body is dynamic, in which the body in the system is in motion where there is a presence of acceleration and the study of the body in that state is studied according to time, velocity, displacement, speed of the body in a particular linear direction or in any certain direction, with an involvement of forces acting on the body or any applied load.

The knee joint is one of the most important joints in the human body. The knee joint is also called as the hinge joint which performs lots of activities like standing, walking, sitting, flexion, extension, with bending of knee etc. with different loads acting upon it with a certain pressure[17]. Knee joint in a human body is made up of mainly 3 components those are tibia, femur and patella with a presence of deformed body. People suffering from knee joint pain and any injury to knee risking everyday and in sports activity leads to occurrence of wearing and tearing on the knee joint. Failure and improper functioning of knee joint due to defect occurrence in the knee may lead to operative solution i.e. removal of components of the knee with an artificial implant termed as knee prosthesis. Examination of defect in knee can be done by X-ray and CT scan as well as with MRI imaging. Mostly knee replacement is done through a small incision, small as 3-4'[18]. According to the defect and failure condition total and partial knee replacement is carried out. In total knee replacement a large implant is inserted in place of the knee joint which favors long term durability and biocompatibility. In spite of excellent working and result it frequently fails in around 4-5 yrs due to chronic inflammation of generated wear particles which results in implant failure giving defective outcomes. Those wear particles interact with the immune system leading to toxicity affects in in- vivo[19]. Due to this hypersensitivity reaction occurred from immunotoxic. Ni, Co, Cr are common sensitizer but when comes in contact with Ti and its alloy they show hypersensitive reaction leading to corrosion and wear of metal implant. The usefulness of material tested according to hypersensitivity of the material as respect to the sensitizers CoCrMo towards the implant material and checking its reliability of the properties of the implant in the target site and its compatibility and durability checking its toxicity rate. Partial knee replacement is done by two methods i.e. unicompartmental partial knee replacement and tri/bicompartmental partial knee replacement. In unicompartmental partial knee prosthesis a Unicondylar fixed bearing knee implant, which is the most commonly used modeled prosthesis or a mobile bearing knee implant. Bi or Tricompartmental partial knee implant consists of one or more component of knee causing less damage to any healthy ligament during the implantation procedure[20].

Dual Articulating Total Knee Prosthesis consist of femoral component, with that a tibia tray and a movable plate. Femoral condyle has lateral and medial condyle and near an automatic mechanical curvature at the articulating surface. This kind of prosthesis provides full flexion and extension without any dislocation of the inserts and with a rear physiological near articulating motion where the stress concentration at the articulating surface is neglected. Articulation mostly occurred at the femoral and tibia insert surfaces. Thus stress concentration calculated at the knee prosthesis inserted region which gradually reduces leading to less loosening of prosthesis and the durability of the fixed implant will increase. With a large contact area throughout the range of motion of knee leads to reduction of stress concentration and the wearing of the implant components. Cruciate ligament makes a greater range of motion possible than the conventional type of total knee replacement prosthesis which is now a day's modeled only a number grossly 140 implants were designed. Relationship in between the concave and the convex surfaces present at the lower surface are of the joint with the articulating surface and the fixed bearing tibia tray convex surface with the articulating upper convex surface all those interfaces between the convex and concave surfaces makes it difficult for the implant to get loosened and cause wearing effect. It provides stability the knee joint during both flexion and extension of the knee with implant and gives proper rotator motion[24].

Knee Replacement Implant Materials:

Implant model designed consists of a flat metal plate and stem implanted inside the tibia and there is a plastic material for the fixation of the metal implant with the bone, i.e. a UHMW polyethylene and with that there is a counter metal plate fit around the end of the femur. Generally, all the components of the knee implant are made up of metal and their alloy. Polyethylene is used for the articulation of tray surface in between the joint with reduced level of wearing to the implant. Materials used for the designing of those knee implants are as follows [25]:

1. Stainless Steel (SS): Most common SS used to design the knee joint implant is 316L SS. It is mainly made up of iron, but has various materials with a composition of metals like chromium more than 11%, molybdenum about 2-3%. It has limited ability to withstand corrosion effect in in-vivo condition, thus it is not preferred frequency while designing of the implant, butt used in designing of knee implant which can be used as temporary implants such as screws and plates.
2. Co-Cr Alloys: These alloys are tough, hard, having high tensile strength, corrosion resistance, less wear affect and posses better biocompatibility. Added with various metals, molybdenum increases the strength of this type of alloy. It is widely used in designing of metal knee implant. Titanium and cobalt chrome are widely used metals in case of knee implant designing. But the use of this metal implant becomes lesser as many patients complain allergic reactions due to the formation of tiny particles of cobalt-chromium while movement of the joint. Those tiny particles released reacts with the body fluid causing allergic effect.
3. Ti-Ti Alloys: Pure titanium material possesses high tensile strength which is generally not that much necessary for the modeling of the knee implant. Ti alloys have specific biological properties such as they are biocompatible in nature with that they show high haemocompatibility. Mostly Ti alloy is Ti6Al4V for knee implant. This metal alloy are corrosion resistance, shows less wearing affect, non-toxic, high tensile strength, posing lower density, low modulus of elasticity as compared to other metal used for designing of the knee implant.
4. Uncemented implants: There are certain implants which directly being fixed to the bone surface, so as bone growth on the surface will increase as the fixation site. For this purpose Ti implant is coated with a cement material so that the bone can grow into the implant surface.
5. Tantalum: Have excellent physical, mechanical and biological properties showing flexibility, corrosion resistance, tensile strength and biocompatibility. A new porous substance has been

made of tantalum named **Trabecular Metal**. It contains pores, the size of which makes this material very well for bone in-growth. In addition, Trabecular Metal has an elastic nature which aids bone remodeling.

6. Polyethylene: The tibial and patellar components in knee replacements are made of polyethylene. Wear is less of a problem in knee implants as the bearing surfaces are flat and do not result in the same kind of wear. The use of the Ultra High Cross Linked Polyethylene (UHCLPE) or Ultra High Molecular Weight Polyethylene (UHMWPE) reduces even the minimal wear enabling the knee implants to last for a much longer time.

TABLE 1: Properties of Biomaterial used for knee implant

Material	**Density (g/cm3)**	**Elastic Modulus (MPa)**
Cobalt-Chrome alloy	8.5	7-30
316L Stainless Steel	8.0	230
CP Titanium	4.51	200
Ti6Al4V	4.40	106
Bone	1550(kg/m3)	1×10^5

From the above study it was found that Ti-Ti alloy i.e. Ti6Al4V shows best biocompatibility and haemocompatibility within the human body. It has outstanding corrosion resistance characteristic, and this degree makes them inert biomaterial, which implies there will be no change after implanting it inside the body. Another detail that makes titanium and its alloys, as a good biomaterial, is their compactness. So from above implant designed materials specification and properties Ti6Al4V has been taken as the material property for this experimental process i.e. stress analysis of knee implant.

Scope & Objective

The literature study reveals that the important factors affecting the movement of knee joints are magnitude of ground reaction force, position of the knee relative to stress tensor and movement of the femur, tibia and patella. In spite of the biomechanical events associated with each part, the main factor that affects the activity of all parts is stress magnitude which is required to be determined during different types of knee activities. In the current study we have planned to use force plate method of analysis for finding the stress magnitude. In order to fulfill our objective we have designed knee implant using CAD followed by 3D finite element analysis using ANSYS. Thereafter, we would like to undertake stress analysis for each portion of the implant which is likely to be generated upon movement. Finally, we would like to compare the stress generated from knee joint and knee implant to verify their homogeneity in magnitude of stress analysis.

1. To determine the stress magnitude using force plate with different knee activities
2. 3-D finite element analysis of knee joint using ANSYS
3. To design full model of knee implant using CAD
4. To perform stress analysis of knee implant
5. To study the stress magnitude of knee implant and knee joint and their comparison

CHAPTER- 3

Materials and Methods

SOFTWARES:

1) CAD (Computer-Aided Design)
2) SOLIDWORKS
3) MESHLAB
4) ANSYS v13.0 (Analysis System)
5) BIOWARE (Force plate Analysis)

MATERIALS:

1) Force Plate -9260AA6 , KISTER company
2) X-ray Image
3) Ti6Al4V metal implant
4) UHMWPE

METHOD:

Work Plan Flow Chart-

- Structural analysis of knee joint
    - Gait cycle
- Force plate analysis
    - Comparison of stress result of experimented individual

↓

- 3-D CAD modeling of knee joint
    - Reduced/Individual model Stress analysis
    - Complete model stress analysis
    - Load Applied: 1400 N

↓

- 3-D FEM of knee implant in CAD
    - Stress analysis of implant(Ti6Al4V)
    - Forces: Vertical Forces
    - Load (N): 540, 590, 640, 690, 740
    - Angle (Contact area) : 10°,30°,50°,70°,80°,90°
    - Stress analysis of knee joint without implant
    - Stress result comparison

Methodology:

1. Structural and Dynamic analysis of knee joint:

A. Gait Cycle:

Human gait cycle refers to the movement accomplished through the motion of human lower and upper limbs. Gait cycle is defined as the biphasic forward propulsion of center of gravity of the human body, in which there are alternate sinuous movements of different segments of the body with less expenditure of energy. Different gait patterns are characterized by differences in limb movement patterns, overall velocity, forces, kinetic and potential energy cycles, and changes in the contact with the ground surface. Gait cycle is followed by two positions, i.e. stance and swing; where stance is the position of the foot touching the ground and swing is the position where the foot is above the ground.

Dynamic analysis of knee joint

Force plate is employed for the dynamic analysis of stress in a knee joint. In this procedure 10 different individuals were asked to perform certain dynamic physical activities over the force plate. Force plate act as a piezoelectric force plate which is very sensitive. Force plate is attached to a DAQ having 8 channels which feeds the recorded data that to the computer to which it is attached to.

Software used in force plate is BIOWARE. Sampling information input to the system:

- Length = 10 secs
- Rate = 1000 Hz
- Direction control = Forward
- Weight = in N
- Force applied in = Frictional forces (Fx, Fy, Fz)
- Moments = Mz in Nm

Dynamic activities performed at force plate:

- Static Condition
- Simultaneous bending of both knees
- Walking in the same position
- Fast walking
- Jumping on the force plate

Individuals were selected according to different heights and weight and test was performed. Stress analysis results were recorded in the computer and analysis was done with the help of BIOWARE software. The results were plotted in the graph and analysis, comparison was studied.

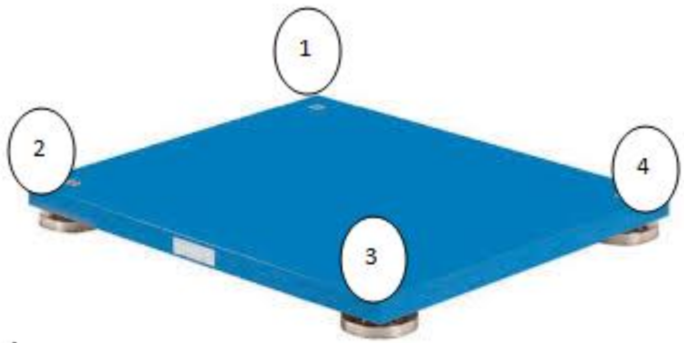
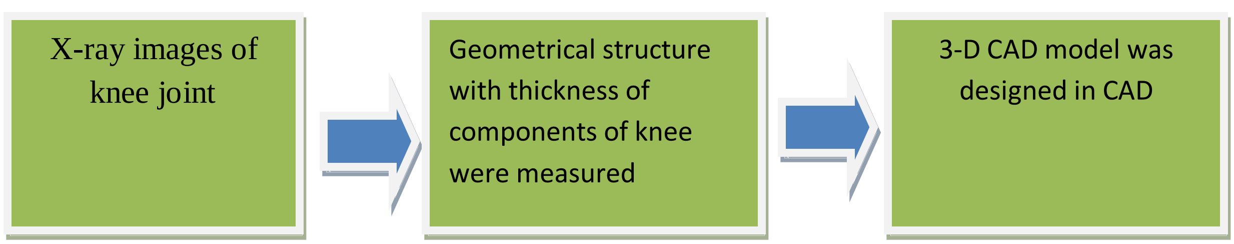


FIGURE 1: Force plate (960AA6)

2. 3-D Finite Element Analysis of Knee Joint

3-D FEM of the knee joint was designed using CAD modeling tool. From the X-ray medical report published on the structure and geometry of the AC, with that thickness of the patella, tibia and femur were noted to construct a 3-D model of the knee according to the gathered information on the geometrical parameters of the knee joint.



2.1 Modeling of Knee joint in CAD

Thickness of different components of the knee was collected from an X-ray image of the knee joint. According to the report, thickness of AC was found to be 2.30±0.2 mm (31±2 yrs old) and 2.32±0.14 mm (69±2 yrs old). As the thickness of components was found as a pseudo prototype of the knee joint, model was designed in CAD where the thickness of AC with femur as 2.31 mm and tibia as 2.30 mm, keeping modulus of elasticity, E=15 MPa and Poisson ratio as 0.445. The CAD designed model was saved in (*. dwg) format.

SOLIDWORKS:

Solidworks is a modeling software as like CAD. Solidworks could be a Para solid-based solid creator, and utilizes a constant feature-based approach to form models and assemblies. In the above discussed section of modeling of the knee joint in CAD, 3D model of the knee was designed. After the model being designed in CAD, it is imported in SOLIDWORKS from where the model material properties are imported, its dimensions are set and if any model part is not needed for the analysis purpose it is being removed in Solidworks workbench. Refined model is then exported to ANSYS 13.0 in (. IGES) format for further analysis work.

A. Finite Element Analysis of Model

CAD model can be directly imported to ANSYS for its finite element analysis.

Step 1: ANSYS was opened from the start menu of PC and mechanical APDL from the menu bar was selected.

Mechanical APDL → Menu bar → Files → saved model was selected.

The model was imported for meshing. Global size control mesh was selected for the model and mesh result was saved as *mesh.db.

Step 2: Clicking on, the solution palette and specific loads were defined, then loads were applied on selected vertical and media site of the joint.

Step 3: Clicking on, all of the DOF with all the constraints applied. Upon load application, structural pressure was applied on the AC linked femur and tibial site.

Step 4: Then the solution palette was selected for current designed model, where nodal solution was selected and Von-Misses [SEQV] was selected.

Step 5: Clicking the reaction solution palette, total deformation with stress magnitude was generated and recorded.

MESHLAB

Meshlab is a free and open-source software. It is an advanced 3D mesh processing software system which is well known in the more technical fields of 3D model development. It is an open-source general-purpose system aimed at the processing of the typical not-so-small unstructured 3D models that arise in the 3D scanning. The automatic mesh cleaning filters include removal of duplicated, unreferenced vertices, non manifold edges, vertices and null faces. Remeshing tools support high quality simplification based on the quadratic error measure, various kinds of subdivision surfaces**.** In some cases due to presence of pores in the model meshing became difficult, in such cases MESHLAB become helpful to carry out the meshing task and the model. Model imported in Meshlab in .stl format. Then remeshing is done using filters, reducing faces, quadratic nodes, etc. After that model is exported as .stl file which is later on imported to SOLIDWORKS after which it is exported to ANSYS 13.0 for analysis work.

B. Full and Individual Model of knee

As discussed in the **section A** of FEA of CAD model, knee joint stress analysis was performed in ANSYS taking the full model of knee and reducing the knee joint into its different individual components as femur, tibia, and patella. In individual modeling of knee we considered the femur, tibia and patella over which a specific amount of load was applied, i.e. 1400 N and stress analysis were performed on the Nodal Solution of ANSYS taking all of the DOF in consideration and in all the components of the plane (X, Y, Z – components). Same as, full model of the knee joint was imported in ANSYS for stress analysis where generally patella, femur and tibia were taken into account and nodal solution was found. In a full model FEM analysis femur was kept in static condition (rigid body) with applied load on each of the components is 1400 N. Full model analysis was done with low density meshed, which can be compatible with the designed model and was performed in a simplified manner.

3. 3-D CAD model of knee joint with implant

A. Structural Analysis of Knee implant

As discussed in **section 2.1** CAD model of the knee implant was designed with material property used in as the alloy specifically Ti6Al4V and UHMWPE as plastic material. CAD designed model of the knee implant was imported to ANSYS for structural analysis.

In this case, analysis was done on the workbench of ANSYS a static structural form. Mostly ANSYS use FEA for 3-D model. Material properties used in for the design prototype of the knee implant were mentioned in **table 2**.

TABLE 2: Material properties for design prototype of implant

Properties	Bone	Ti6Al4V	UHMWPE
Young's modulus(MPa)	1×10^5	1.06×10^5	2000
Poisson ratio	0.45	0.29	0.44
Density(Kg/m^3)	1550	4400	-

For the static structural analysis of designed model, ANSYS v13. 0 was used in.

Step 1: Open ANSYS v13. 0 software and workbench was opened. Static structural palette was clicked, a new window pops.

Step 2: From the menu bar → file → designed model of the knee implant was imported to ANSYS workbench, static structural analysis.

Step 3: Meshing was performed for the designed model and then generated.

Step 4: Structural analysis palette was clicked; new window pops up i.e. DM (design model) was selected. After that 3-D structure was updated and then generated.

Step 5: Static structural analysis → fixed supports was selected → vertices were chosen → loads were applied.

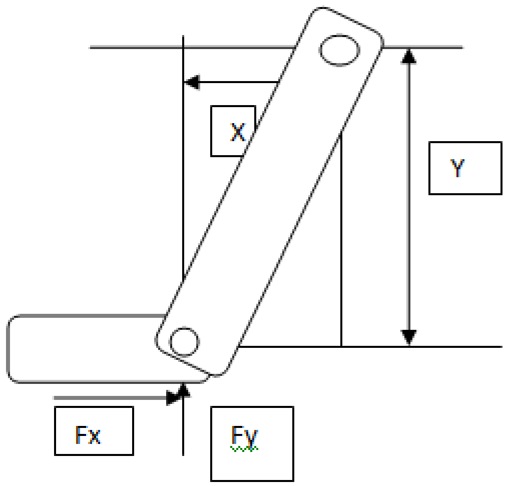
Step 6: On the selected edges specific loads were applied, multiple edges can be selected by pressing Ctrl tab.

Step 7: Select the details for body and components were defined. Now clicking on the solution (AS) palette and solve was selected.

Step 8: Deformation was selected, equivalent stress were chosen and then the model was generated.

Step 9: Solving palette was clicked, selecting different load stress magnitude was observed and results were recorded.

B. Knee joint without implant and result comparison



Fx → Frictional Force

Fy→ Ground reaction force

X→ perpendicular distance along Fy

Y→ Perpendicular distance along Fx

FIGURE 2 : Forces applied to the knee joint

Follow the steps as discussed in the above **section A,** and perform the static structural analysis of the knee joint without implant. In this static structural analysis of the knee joint without implant different loads were subjected i.e. 540 N, 590 N, 640 N, 690 N, 740 N and angle of the contact area as 10°, 30°, 50°,70°, 80°. And stress analysis was performed in both cases i.e knee joint without implant and knee implant.

Initially, stress analysis was performed in knee joint with different load and angles without any implant with vertical forces. Results were recorded.

CHAPTER- 4

Results and Discussion

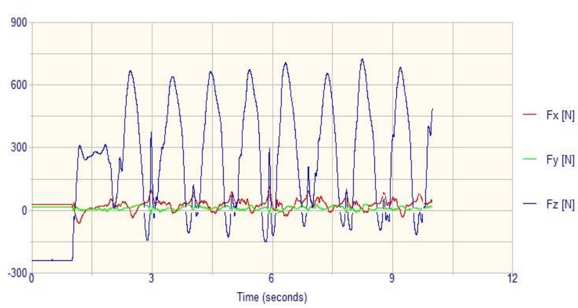
1. Dynamic stress analysis of knee joint

Stress analysis of the knee joint was performed at force plate that provides a preliminary idea of stress magnitude at knee joint when an individual did some physical activity or was in a very dynamic motion. Analysis was performed using 10 individuals of different height and weight. Among 10 output results, best 5 output results were discussed and compared.

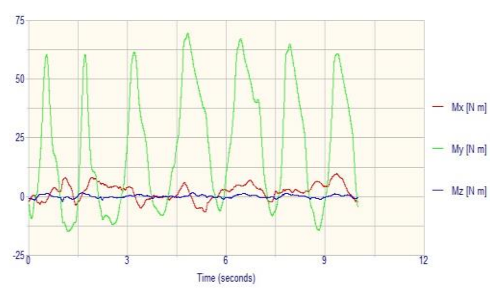
Individuals with varying heights and weight for the analysis of ground reaction force moment determination are shown in **Table 3**.

TABLE 3 : List of individuals with different height and weight

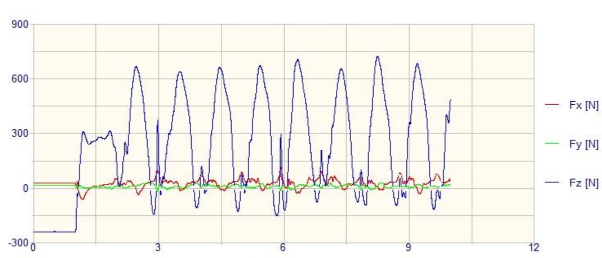
Individual	Height(in ft)	Weight (Kg)
1.	5’4	49
2.	5’0	52
3.	5’8	65
4.	5’11	74
5.	5’5	56

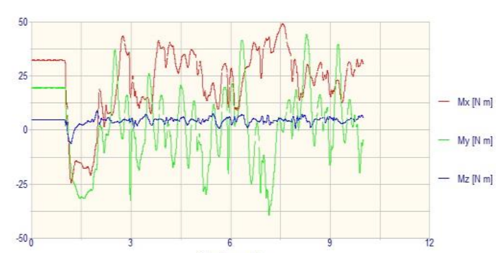


3(a)

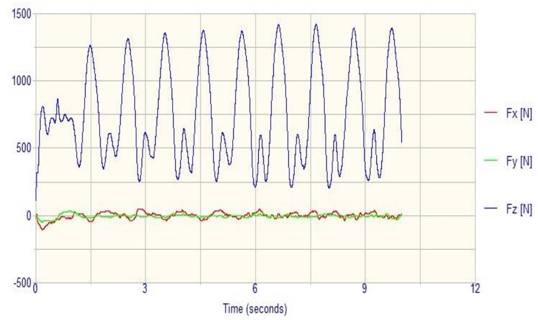


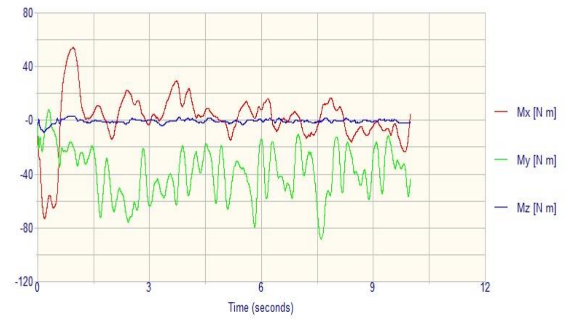
3(b)



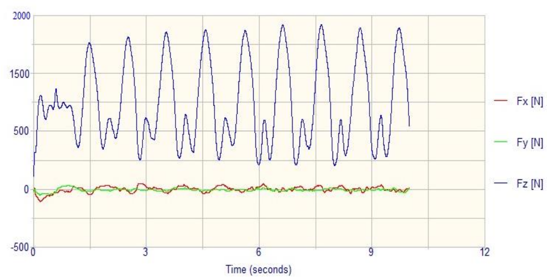


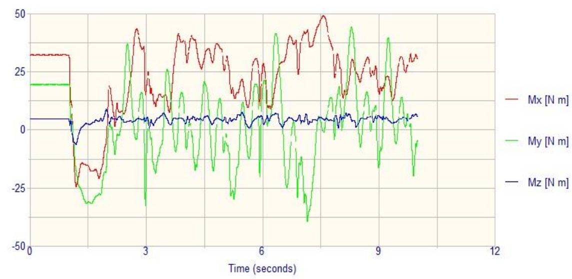
3(c) 3(d)





3(e) 3(f)





3(g) 3(h)

FIGURE 3: Force plate stress analysis 3(a-i)

In the above **figure,** force plate stress analysis is shown where 3(a-g) represents ground reaction forces and moments on the force plate generated due to each individual performance on the force plate. In each graph for force determination, Y-direction represents the vertical ground reaction force, X-direction is for anterior-posterior force, and Z-direction is for the medial-lateral force. All are in the same unit, i.e. N (Newton) versus time period T in Sec. For the study of moment, Mx, My, Mz represents the plate moment about X, Y and Z axis respectively with standard unit N-m versus time period T in sec.

Figure 3(a) represents the ground reaction force determination of individual 1 with height 5’4 and weight 49 kg. In this case the VGRF (vertical ground reaction force) which is Fy, was in the baseline of the spreadsheet. Fx fluctuates over the baseline whereas Fz the medial-lateral force reaches to the maximum peak level of 790 N approximately. Mostly we consider Fz force because while performing the activity of bending both knees simultaneously at same position Fz shows a higher peak as compared to rest of the force plate. Initially two humps occur at the start of the graph generation in the spreadsheet which is due to the foot striking from the ground to the force plate prior to the center of gravity traveling downward. From this we observed that at a particular speed, contact time will be even shorter, but this will necessitate higher peak forces in order to support body weight.

Figure 3(b) represents the moment of the body determined using a force plate. The above graph is for individual 1 which shows that My i.e. the vertical moment showing highest peak of approx. 62 Nm where as moments at Mz lies on the base line and Mx fluctuates over the baseline.
This result shows that with highest VGRF at Fz zone, we found a low moment in Mz zone.

Figure 3 (c) represents the ground reaction force determination for individual 2 with height 5'0 and weight 52 kg. From this graph we found that Fy was in the baseline, Fz fluctuates over the baseline and Fz reaches a maximum peak of 750 N. In this case weight plays an important role as bending knees in the same position on the force plates generates a higher medial-lateral force where as VGRF is in the baseline. With an increase in the speed of activity, distance between the hump peaks gradually decreases.

Figure 3 (d) represents the moment of the body determined using a force plate. Result shown in the above graph is for individual 2 which shows a higher range of fluctuation in the entire axis Mx, My and Mz. In this graph we found that Mx starts from 30 Nm above the baseline and gradually decreases to -25 Nm and then reaches to maximum peak of 34 Nm where as Mz starts from above the baseline and runs over the baseline throughout the time period. Maximum variation is being observed in graph line of My which starts from 22Nm above the baseline and shows a lot of fluctuation within its peak, increasing and decreasing gradually reaching a max. level of 37 Nm and minimum of -30 Nm. Variations in the graph shows wide changes in the acceleration of body motion while speeding up and slowing sown in the activity gradually.

Figure 3 (e) represents the ground reaction force determination for individual no.3 with height 5'8 and weight 65 kg were found that Fz reaches to the max. peak of 1250 N, Fx runs over baseline and Fy lies on 0 N. Here we observe a maximum peak of force in the medial-lateral region which shows that with an increase in load, ground reaction force counteract upon the gravitational force as much leading to increase in max. value of Fz.

Figure 3 (f) represent moments of the body for individual 3 represented on graph sheet which shows that Mx varies from -68Nm to the baseline region, Mz runs on 0 Nm where as My fluctuate from baseline and gradually runs below the baseline and reaches to a minimum peak value of **-**45 Nm. From this peak variation we found that the acceleration of the body varies a lot upon load and velocity of the activity performed over the time period.

Figure 3(g) graph represents the ground reaction force determination for individual 4 with height 5’11 with weight 72 kg where we found that maximum peak was attained by medial-lateral force, Fz reaching to 1750 N, Fx runs over the base line zone and Fy remains on the 0 N. In this case, with increase in height and weight, ground reaction force increases attaining maximum value.

Figure 3 (h) graphically represent moments of the body, i.e. Mx, My, Mz versus the time period (in Sec) where we found that Mx attains a maximum peak of 50 Nm, Mz runs above the baseline i.e. 0 Nm and My fluctuates over a range of values attaining maximum value of 37 Nm and minimum peak of -35Nm. Since we can say that performing activity at the center of the force plate with increase in load leads to traveling of gravity down toward the ground at impact and only changes directions once the speed is slow down.

From the above experimental study, we found individual with maximum height and weight, i.e. individual No. 4 with a height of 5’11 and weight of 74 Kg represents maximum ground reaction force and moment attaining maximum value of medial-lateral force i.e. Fz zone and minimum value of Mz over a time period. With an increase in weight and height of the body force increases 3-5 times exerted to the body while walking and performing any physical activity. Increase in weight is sufficient to exert minimal axial compressive force which can lead to pain in the knee joint.

2. Stress analysis of full and reduced model of knee joint

The load applied = 1400 N

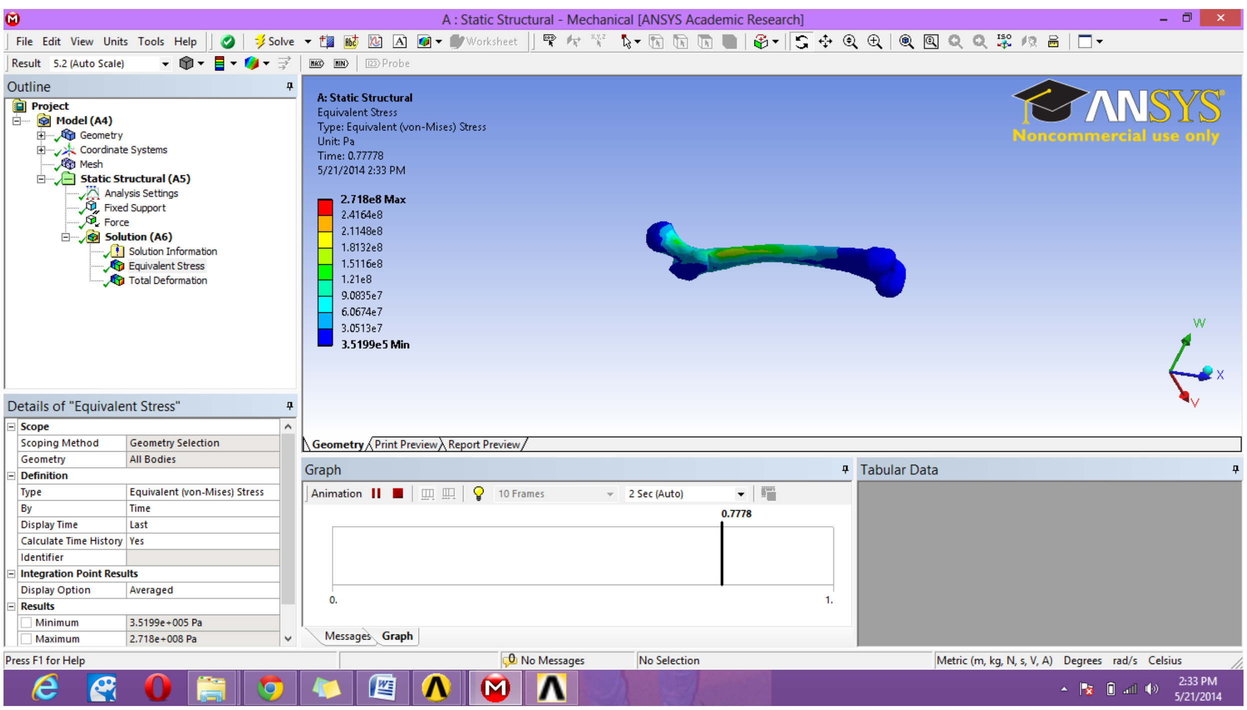
Stress applied = Equivalent stress (Von-misses stress)

The stress magnitude of both full model and reduced model of the knee joint was calculated analytically and the data are represented in **table 4**.

TABLE 4: Result of Reduced and full model stress analysis of knee

	Reduced model stress (Pa)			Full model stress (Pa)		
components	X	y	z	x	Y	Z
Femur	3.52E+05	2.53E+05	3.56E+05	2.54E+05	9.22E+04	2.25E+03
Tibia	50556	12808	19523	27743	16699	43771
Patella	3.28E+05	6.71E+05	3.65E+05	2.13E+05	1.50E+05	3.11E+05

Reduced model stress analysis of the knee joint with specific load is shown in **figure 4**. Such type of model bears significant effect in increasing the accuracy of the result



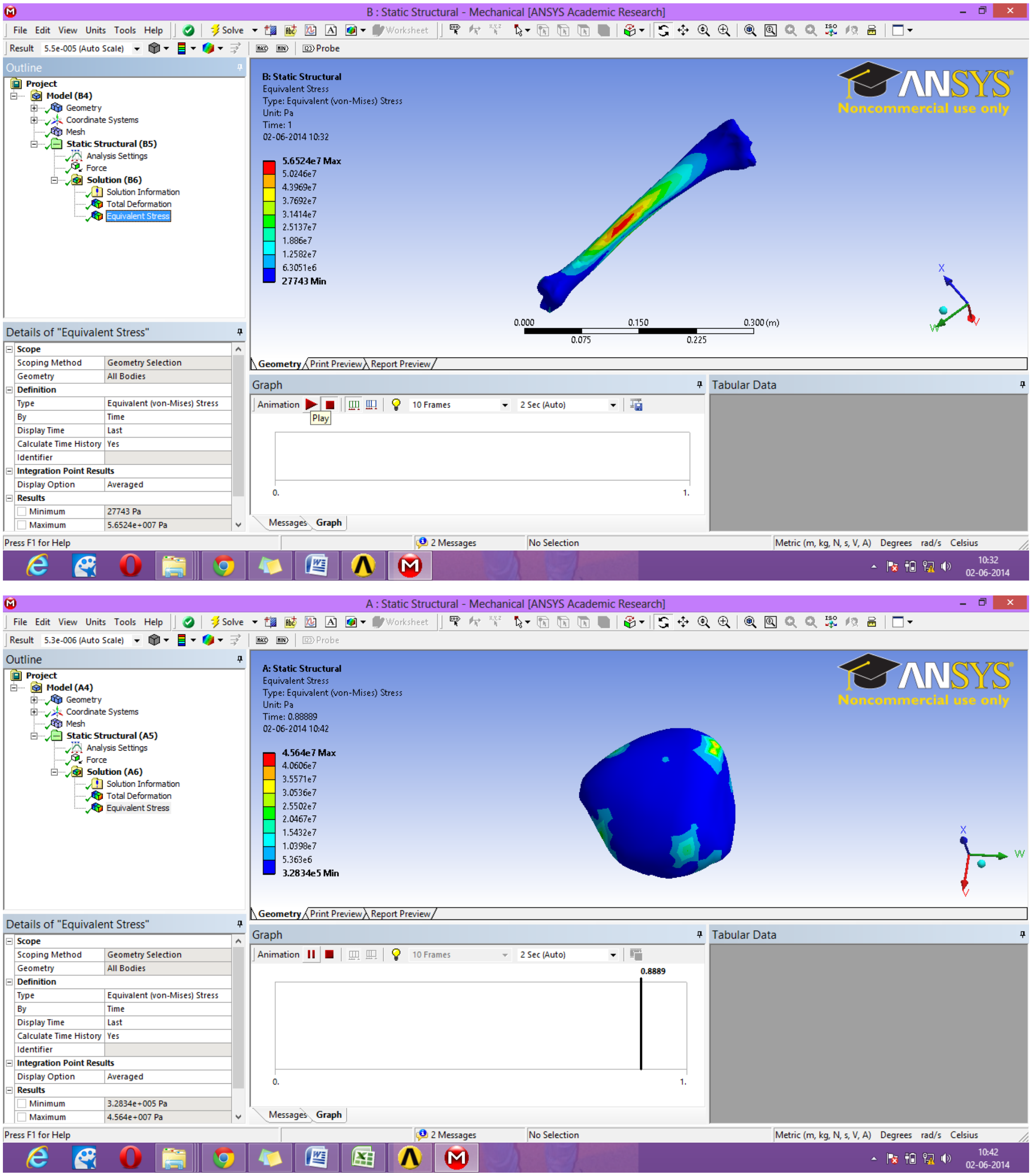


FIGURE 4 Reduced model analysis of knee joint

Figure 4 represents stress analysis of reduced/individual parts of knee joint, i.e. femur, tibia and patella respectively. In this figure mostly analysis part was being shown where the solution information was collected upon importing certain load and examining the equivalent stress magnitude. Here 1400 N force was applied to the parts of knee and stress magnitude was calculated in Pa as standard unit. Femur shows a maximum stress of 2.718e8 Pa and minimum stress of 3.5199e5 in the X- component. Tibia shows 155.03 Pa, maximum stress result and a minimum of 150.67 Pa in the x-component. Patella shows a maximum stress value of 4.564e7 Pa and minimum value of 3.2834e5 Pa in the X-component. In the solution part we can see the maximum and minimum values of knee joint stress analysis. The outcome of the stress analysis of the individual components of the knee joint is represented in a table format.

Forces for different components of the knee joint with varying plane, i.e. X, Y and Z component and their stress analysis outcome is shown in **table 5**.

TABLE 5: Reduced model stress analysis of knee

Reduced model Analysis	Components		
	1400(X-comp)	1400(Y-comp)	1400(Z-comp)
Femur(Pa)	3.52E+05	2.53E+05	3.56E+05
Tibia(Pa)	50556	12808	19523
Patella(Pa)	3.28E+05	6.71E+05	3.65E+05

Table 5 represents the stress magnitude result of individual parts of the knee joint after the analytical work was performed in ANSYS 13. In the above table individual part of knee joint stress magnitude is recorded. Stress value was recorded in the standard unit, i.e. in Pa when a force of 1400 N is applied to the specific models. Here stress result of all the three components by axis was obtained, i.e. X, Y and Z where same force was applied. The tabular data are then represented in the graph.

Von- misses stress of reduced model of the knee joint with specific loads in various vector components of plane shown on table 5 was graphically displayed in **figure 5**. It signifies the stress magnitude at each individual component of the knee joint.

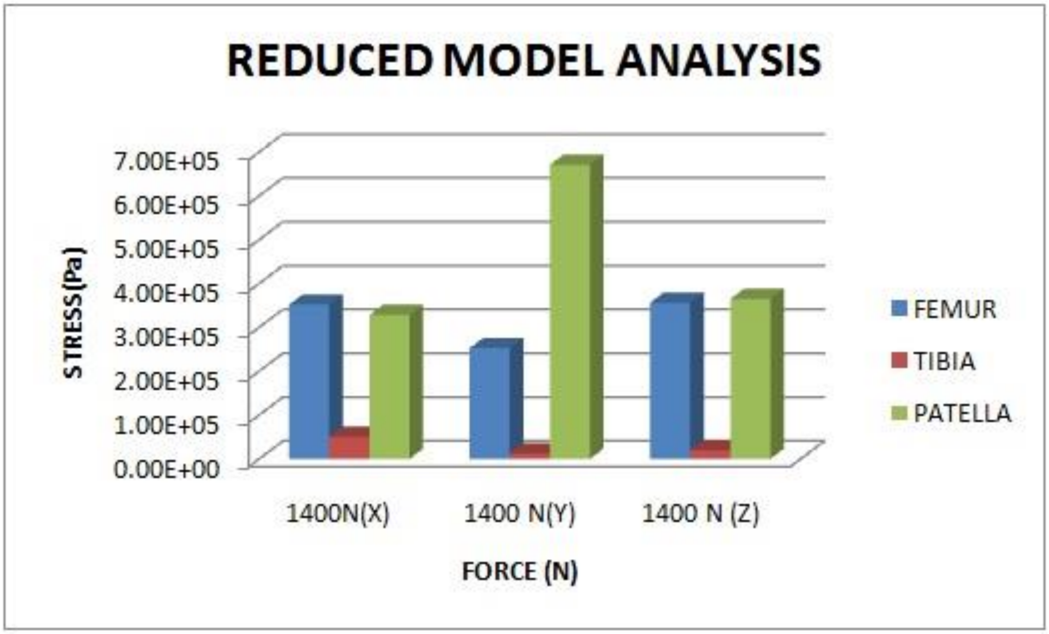
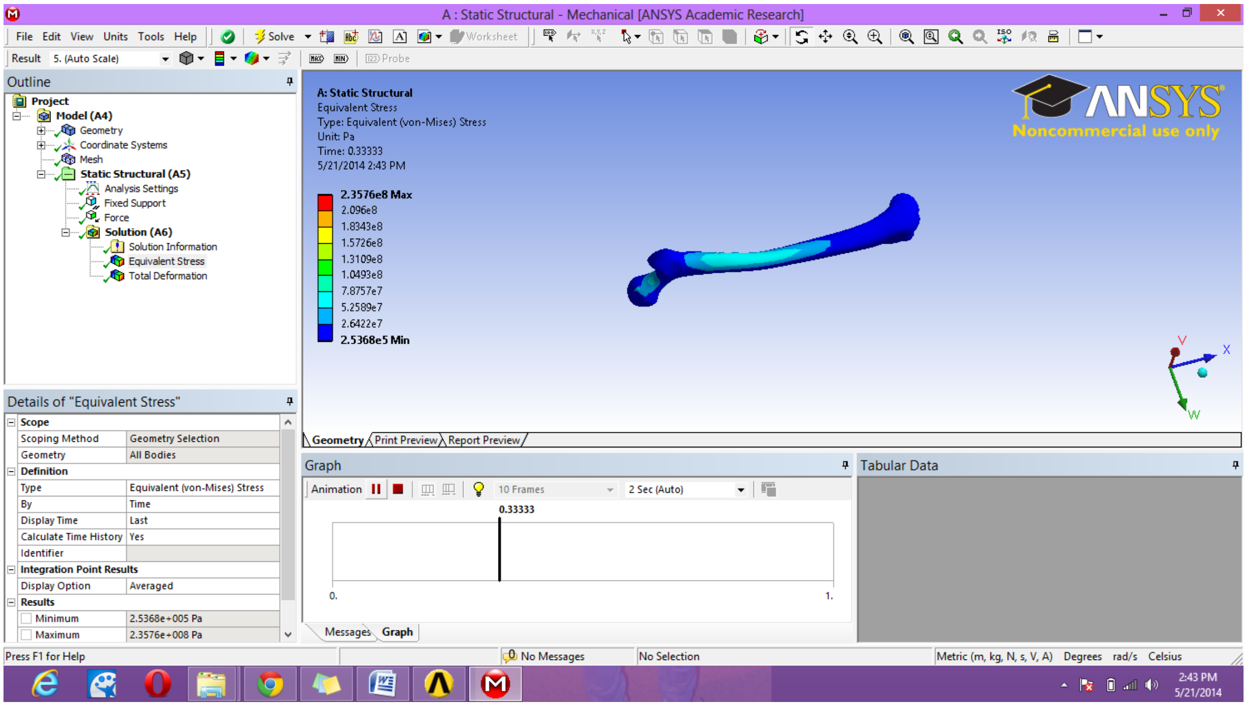
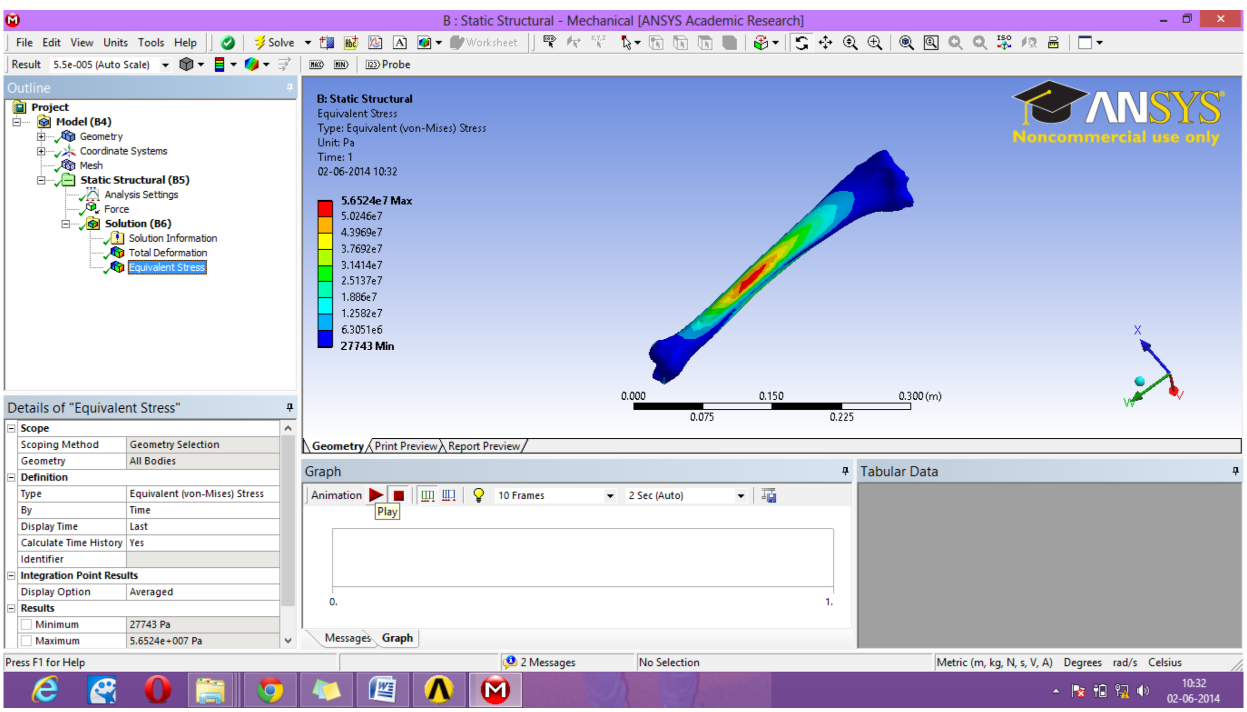


FIGURE 5 : Reduced model stress analysis

Figure 5 is the graphical representation of stress analysis of reduced model of the knee joint. This graph is plotted as stress (in Pa) in the Y-axis and Force (in N) in X-axis. From the graph we observe that, patella attains a high bar value as compared to other part of the knee joint. Patella represented in the green color bar which attains a maximum stress value, upon force application of 1400N in the Y-component. The stress value attained by patella in this case was 6.7117e5 Pa. From this we can predict that upon application of force on the knee joint, patella's deformation increases gradually with increase in load. When a force of 1400 N is applied on the knee joint, deformation range of patella in the Y axis is 584.86 to 258.2.

Equivalent stress analysis of the full model of various components of the knee joint is displayed in **figure 6**. This analysis signifies that how an adult knee joint can bears various load range.





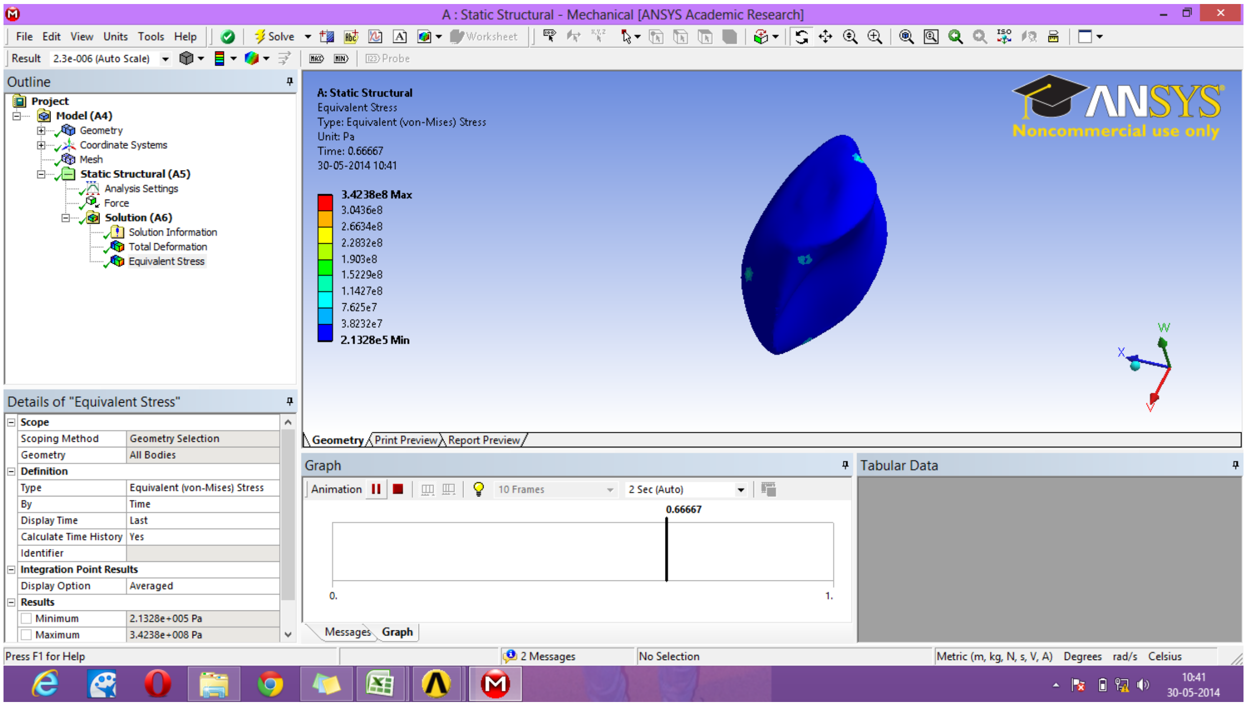


FIGURE 6: Result of full model stress analysis of femur, tibia and patella

Figure 6 represents the stress analysis of the full model of knee joint, i.e. femur, tibia, patella. In this case meshing was performed in fine form with simplified results. Stress magnitude was obtained in Pa when a force of 1400 N was applied to the specific regions of the designed model. Femur maximum stress magnitude in X-component was found to be 2.3576e8 Pa and minimum value as 2.5368e5 Pa. In case of tibia maximum stress value was 5.6524e7 Pa and 27743 Pa minimum stress value in the X - component. For patella maximum stress magnitude was 1160.7 Pa and minimum value as 730.33 Pa. The final outcome of the above analysis is recorded in a table format.

Von-Misses Stress analysis result for full model of the knee joint with specific load of 1400N in various vector components of the plane is recorded in **Table 6.**

TABLE 6: Result of full model stress analysis of knee

Full model Analysis	Components		
	1400(X-comp)	1400(Y-comp)	1400(Z-comp)
Femur(Pa)	2.54E+05	9.22E+04	2.25E+03
Tibia(Pa)	27743	16699	43771
Patella(Pa)	2.13E+05	1.50E+05	3.11E+05

Table 6 represents the result of stress analysis of full model knee joint components, i.e. femur, tibia and patella. A force applied in the above case was 1400 N and each component X, Y, Z was individually recorded for each model. Stress magnitude obtained in the form of standard unit of Pa. Obtained stress value for full model of the knee joint is then represented graphically in **Figure 7**.

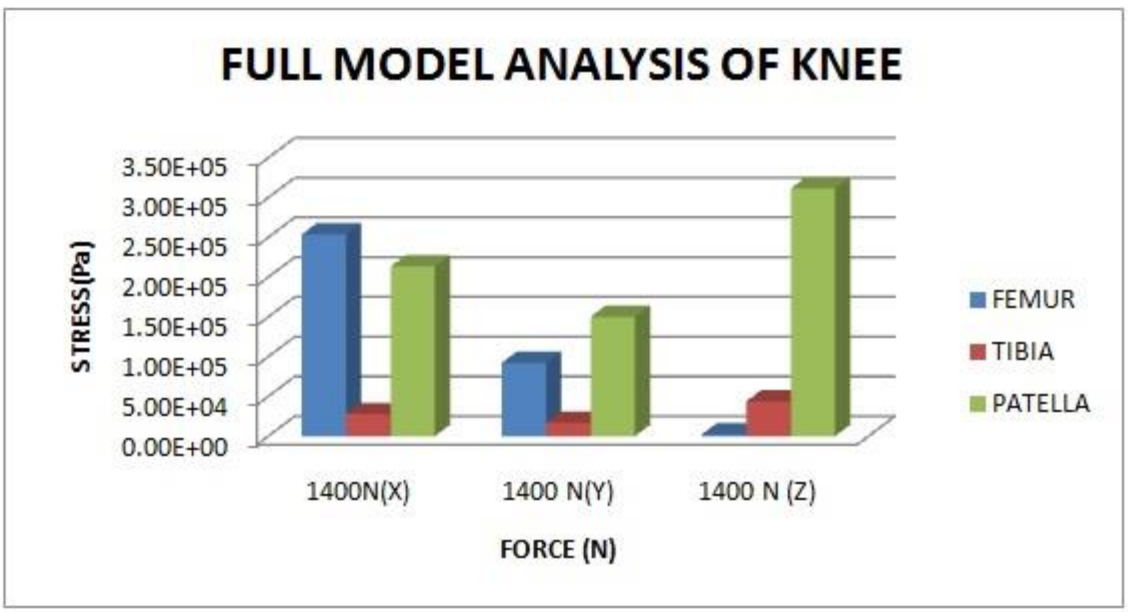


FIGURE 7: Full model stress analysis of knee

Figure 7 is the graphical representation of the full model stress analysis of the knee joint. In the above graph we found that in the full model, stress analysis shows the lowest stress magnitude. Stress analysis of the menisci in full model was ignored because it doesn't affect that much when a load was being applied to the knee joint whereas patella a high range of stress magnitude under load of 1400 N with further increase in load leads to failure of the knee joint. Patella shows a higher bar graph in the Z-component having a stress value of 3.11e5 Pa.

From the above experimental study, we found that in reduced model knee components were analyzed separately, where we found out that the stress magnitude increases with load in all of the components as compared to full model stress analysis.

3. Stress analysis of the knee implant

The equivalent stress analysis result of knee implant at a range of load from 540N to 790 N with changing angle of inclination from 10° to 90° were recorded and the data's are presented in **Table 7**.

TABLE 7: Knee implant stress analysis result

		Von-Misses Stress (in Pa)				
Weight (in N)/Angle	10°	30°	50°	70°	80°	90°
540	8.90E+07	2.40E+08	2.93E+08	9.87E+07	4.08E+08	3.73E+08
640	9.84E+07	2.43E+08	3.54E+08	4.52E+08	4.63E+08	3.64E+08
690	1.09E+08	2.47E+08	3.48E+08	5.15E+08	5.32E+08	3.95E+08
740	1.14E+08	2.53E+08	3.47E+08	5.89E+08	5.95E+08	4.08E+08
790	9.36E+07	2.65E+08	3.49E+08	6.45E+08	6.53E+08	4.40E+08

Table 7 represents the stress analysis result of knee implant recorded in a tabular format upon force application in a wide range, i.e. 540N, 640N, 690N, 740N, and 790N with change in angles from 10°, 30°, 50°, 70°, 80°, 90°. And the equivalent stress was analyzed in standard unit format, i.e. in Pa. In this case, both stress magnitude was recorded only for the X - component. The above result is then plotted graphically.

3D CAD model of the knee with implant after remeshing task performed in Meshlab at an angle of 90° inclination as shown in **Figure 8.**

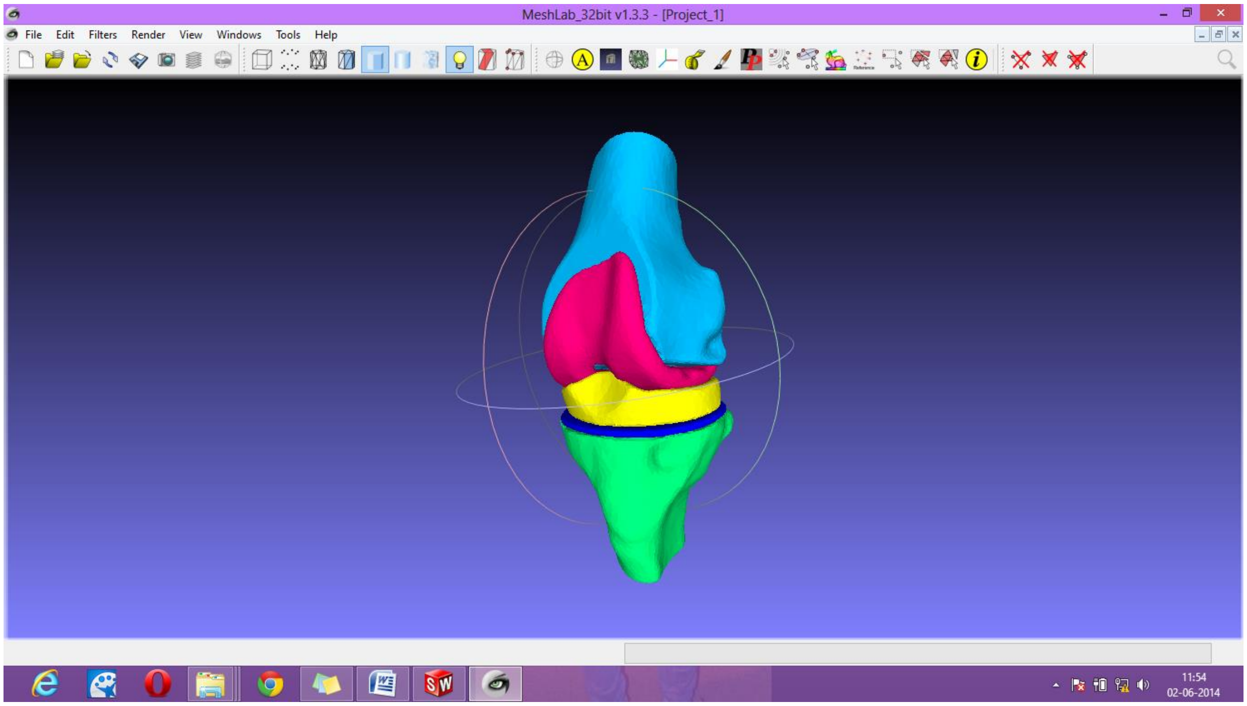


FIGURE 8 : Knee joint with implant

Figure 8 represents knee joint with an implant which was imported in meshlab for remeshing purpose. Meshlab can take model only in .stl format. Different color codes are representing different faces of the knee joint with an implant. Yellow face was the implant tibial tray whereas pink face was implanting metal surface of the femoral component. The model components are then exported in .stl format after the remeshing work is done.

Exported model was saved in .stl format which is then imported in Solidworks where only the implant components are kept and rest faces are excluded. Implant was introduced to the specific material property of Ti6Al4Vand exported to ANSYS in .IGES format.

Von-Misses Stress analysis of knee implant at varying load and varying angles of inclination are displayed in **Figure 9.**

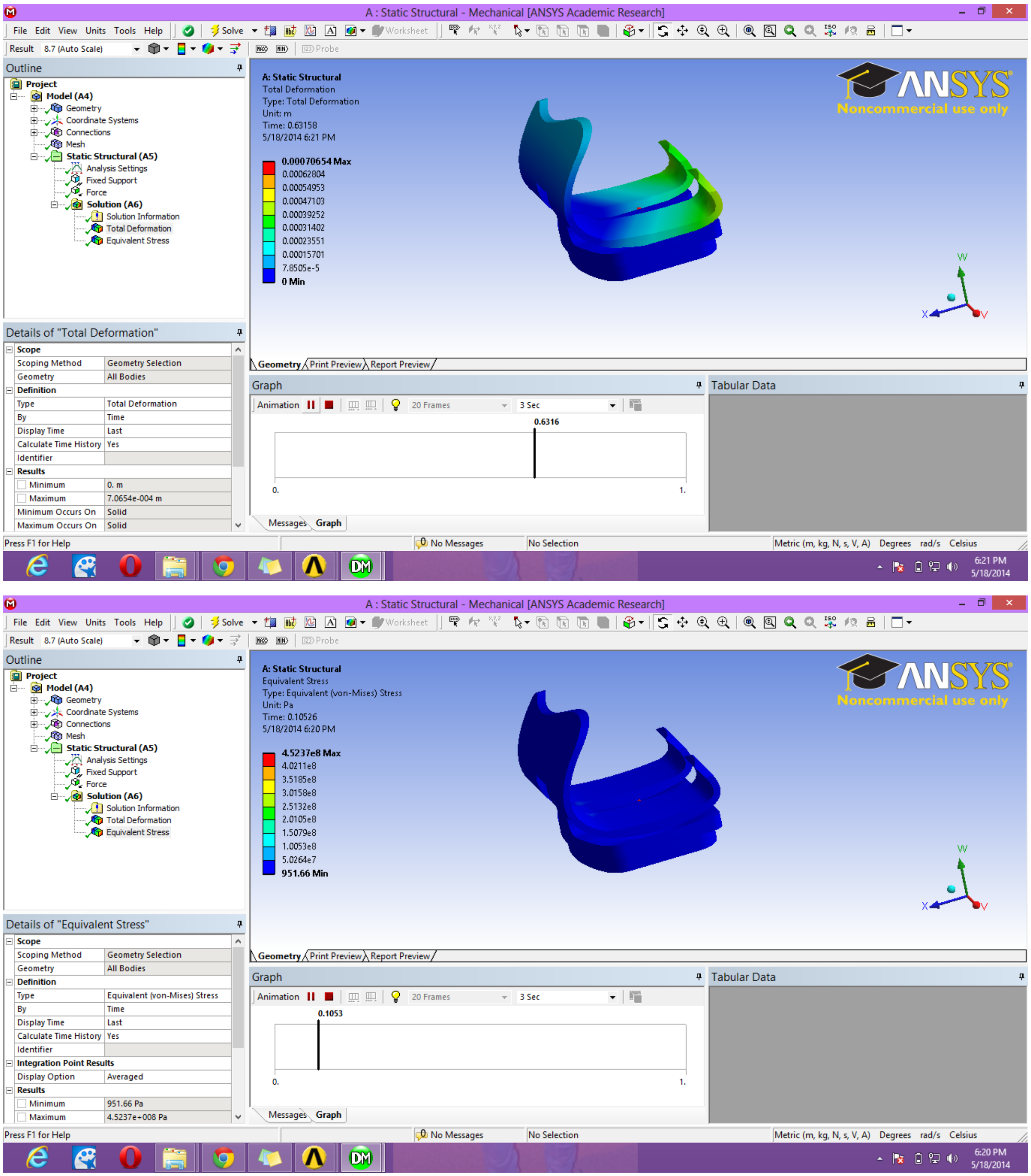


FIGURE 9: Knee implant total deformation and stress analysis

Figure 9 represents the stress analysis of knee implant with varied load and angle. The figure shows the solution part of analysis work where the stress magnitude is recorded. This analysis was performed for only X-component. Force imported to the implant was 540-790 N. The figure also represents the solution of stress analysis of implant with 640 N, at an angle of 70° where stress magnitude obtained was 4.5237e8 Pa maximum in X-component and 951.06 Pa minimum value. Similar analysis work was performed with different load and different angles and thus, the result were recorded. The recorded stress magnitude value was then represented graphically.

Comparative result displaying the equivalent stress magnitude of knee implant at varying load with varying angle of inclination is shown in **figure 10.**

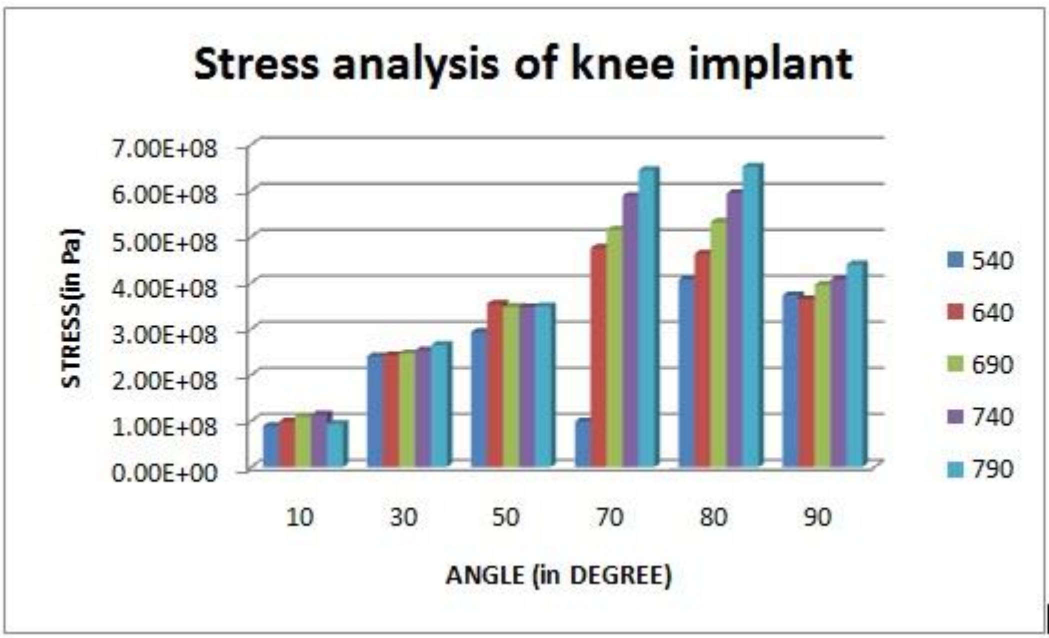


FIGURE 10: Stress analysis of implant at different angles and load range

Figure 10 graphically represents stress analysis of knee implant with different load with a variable angle. From the graph we can observe that the stress analysis of the knee joint with an implant was performed using ANSYS v13 where we found that upon application of a range of load, i.e. 540-790 N at different angles of inclination, at the contact area of the femur, tibia and patella with the cartilages. Stress magnitude was found to be stable at 10°-50° attaining maximum value of 1.27E+08 – 6.11E+08 Pa where low wearing occurs. In the steady state of knee i.e. at 90°, low stress value of 1.28E+08 Pa is attained by the implant. Whereas at 70°-80° stress magnitude rises to a high peak with load reaching stress value of 6.45E+08 Pa and 6.53E+08 Pa respectively.

Stress magnitude of the knee joint after the analytical work was performed under certain load and varying angles in ANSYS are recorded and results are displayed in **Table 8.**

TABLE 8: stress analysis of knee joint with vertical forces

Weight(N)/Angle		Von-Misses Stress (in Pa)				
	10°	30°	50°	70°	80°	90°
540 N	6.69E+06	4.89E+08	6.56E+07	9.65E+07	3.25E+08	1.53E+08
640 N	7.32E+07	4.36E+08	6.89E+07	2.13E+08	4.26E+08	1.05E+08
690 N	6.25E+07	4.97E+08	7.47E+08	2.23E+08	4.21E+08	1.13E+08
740 N	1.16E+08	5.11E+08	5.20E+08	2.35E+08	5.57E+08	1.26E+08
790 N	1.27E+08	5.65E+08	6.11E+08	2.56E+08	5.64E+08	1.28E+08

Table 8 represents the recorded data values of stress analysis of the knee joint without implant with varying load and angle. Stress magnitude was recorded in Pa unit when the force applied to the model is in Newton (N). The obtained data are plotted graphically.

Equivalent stress analysis of knee joint without an implant was performed in ANSYS workbench at various angles for different loads is displayed in **Figure 11.**

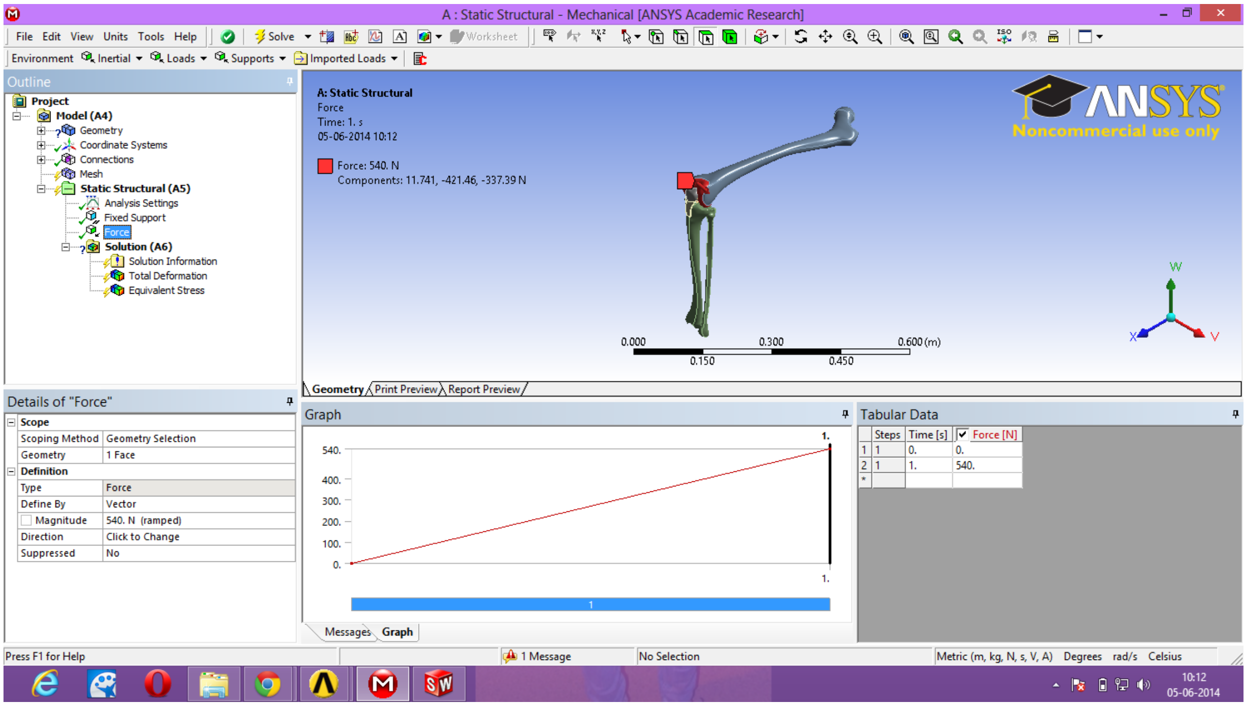


FIGURE 11: stress analysis knee joint without implant

Figure 11 shows the analysis work of knee without implant where the solution part was performed. Where force was defined by vector, i.e. in only one component. Force was applied vertically with standard unit Newton (N) and stress magnitude is recorded in Pa. Force applied on the knee joint was 640 N and the resultant stress was found to be 1.28E+08 Pa at 90°. Similar analysis was performed with varying load and angles. Final results were recorded in tabular format.

Von-misses stress result for knee joint without an implant with changing angles at different loads was displayed in a comparative chart which is shown in **figure 12.**

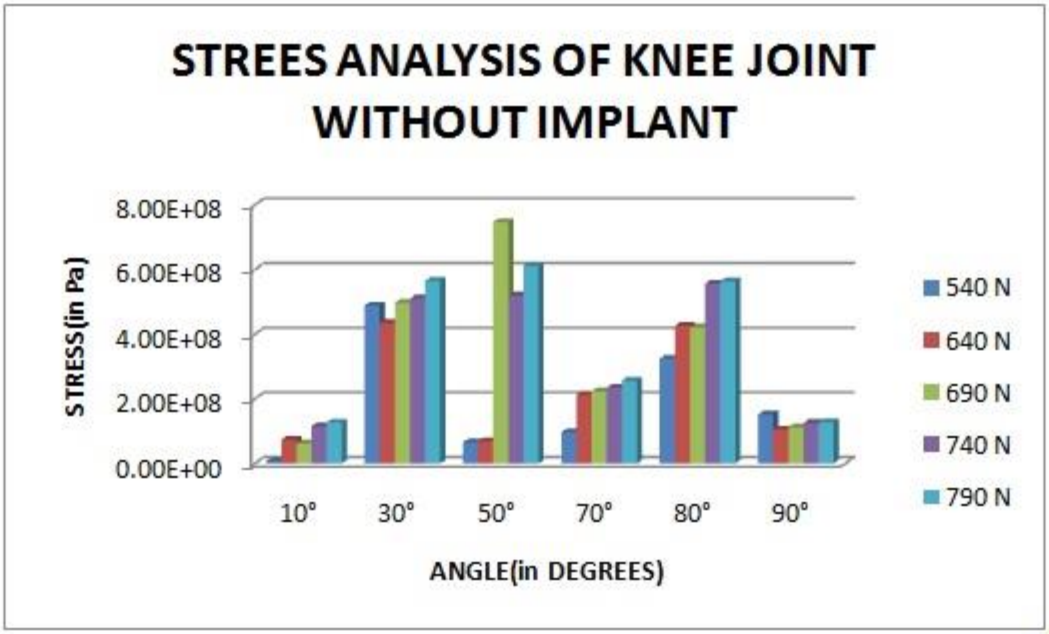


FIGURE 12: Stress analysis of knee joint without implant with vertical forces

Figure 12 represents graphical interpretation of recorded values of stress analysis of knee joint with varying load from 540 N-790 N and varying angles. With vertical forces, we found out that at load of 690-790 N wearing affect become lesser at 10°, 70 °, and 90°. At 50° upon a load of 90 N stress value attains a high peak bar with 7.47E+08 Pa. As load increases wearing occur and while running and walking stress magnitude vary that causes injuries to the knee joint.

Upon comparing both the results of stress analysis of the knee with implant and without an implant, we observe that beyond 50° implant starts tearing with gradual increase in the load. In 10°-50° flexion, knee implant posses less stress with a load of 640-790 N. At 90°, the knee implant was in steady state which cause less wear affect in the implant.

In this project work mostly stress analysis of the knee joint and its implant has been done. With a preliminary knowledge obtained after the study of force plate analysis for the determination of ground reaction forces and moment of the body, by performing certain physical activities on the force plate with the help of different individuals of varying height and weight. It was found that individual with maximum height and weight, i.e. individual 4 with height 5'11 and weight 74 Kg shows the highest peak range of medial-lateral force value of 1750 N and lowest moment of -35 Nm. After this, CAD model of the knee joint was designed and its reduced model and full model stress analysis were performed separately and the obtained stress magnitude results were compared. The final outcome of this study was that stress analysis of full model was observed to be lesser as compared to individual model of the knee joint. Patella shows maximum bar value in the Y - component of reduced model which was 6.7117e5 Pa and in full model analysis patella shows the highest bar value 3.114e5 in the Z-component. From the above analysis, we observe that upon an increase in load in the knee joint, patella starts deforming first as compared to the other knee joint component. After that 3-D model of the knee joint was designed and its implant was modeled. Stress analysis with a rage of load with varying angle was performed on knee implant and knee joint without implant and the recorded stress magnitude results were compared. With a load range of 540N to 790 N and change in angle from 10° to 90° it was observed that knee implant can sustain a load of 540-640 N with an angle of 10°-50° with a stable stress value of 1.27E+08 – 6.11E+08 Pa at steady state of the knee, when the knee is in 90° position stress value reaches to 1.28E+08 Pa. When this study was compared with stress analysis of the knee joint without implant, it was observed that there is wide variation in the stress magnitude with the increase in load values with changing angles. At load of 690-790 N, wearing effect becomes lesser at 10°, 70 °, and 90°. At 50° upon a load of 690 N stress value attains a higher peak bar with 7.47E+08 Pa. From this we can conclude that knee implant can be designed in such a manner that it can uptake maximum load with varying angle of inclination.

CHAPTER- 5

Conclusion

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The static structural analysis of the knee joint has a great significance, as these analytical results provide us a wider knowledge about the mechanical behavior of the knee. Performing stress analysis as a simulation method instead of intrusive methods is one of the important part of biomechanical study for different 3D models. The study reveals that the stress analysis work performed by X-ray images which help us to obtain a rough geometry of the knee joint. Analysis work was supported by ANSYS 13.0 which ensured that only desired and specific parts of the knee joint are involved in the designing and simulation of the model. Converting the specific geometry designed in CAD into Solidworks and Meshlab, and importing it in STL format can be used to validate the knee model along with finite element analysis. The material assignment was performed by Solidworks. For designing 3-D CAD model of the knee joint and knee implant, total CAD software operation was used, to examine the overall geometry of the designed model. It has been established that the angular stability of the knee implant can be improved through this analytical approach. Thus it has been demonstrated that this analysis paves the way for incorporation of different materials based on stress work.

Future Prospects

Based on this study, the experimental work on fabrication of the knee and hip implant can be performed. This will give a definite approach for fabrication of implant in less no of experiments in a cost effective manner.

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